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SYNTHETIC POLYMER FIBRE REINFORCED CONCRETE SLABS AND THEIR EFFECTS ON THE MECHANICAL PROPERTIES: A REVIEW

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ABSTRACT

Concrete is a ubiquitous construction used extensively in structural engineering due to its high compressive strength and low cost. Concrete is an inherently brittle material, this lowers its strength and strain capacity. However, concrete has a number of shortcomings such as shrinkage and cracking, very low tensile and flexural strength, high brittleness and low shock resistance. The use of synthetic polymeric fibers within concrete helps to alleviate some of these shortcomings in concrete slabs. Furthermore, synthetic polymeric fibbers are lightweight and help prevent the development and growth of cracks in concrete slabs. Synthetic polymers such as polypropylene, polyethylene, polyamides and olefins have been used in concrete slabs with some success. The workability and strength of fiber reinforced concrete slabs is dependent on the fiber loading and fiber aspect ratio. The purpose of this study is to review synthetic polymer fiber reinforced slabs and their effects on the mechanical properties.

KEYWORDS: Concrete Slabs, Mechanical Properties, Synthetic Polymeric Fibre & Workability

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Original Article

1. INTRODUCTION

Concrete is a particulate ceramic composite, in which the aggregates are embedded in a microcrystalline silicate resin. The ingredients of concrete consists of cement which is the matrix, coarse aggregates as the framework, fine aggregate and fly ash if any as filler material, water and other specific additives. Concrete slabs are inherently brittle material; this lowers its strength and strain capacity under tension[1]. Intertwined with this lack of toughness is the tendency of concrete slabs to crack in both its plastic and hardened state. Cracks and fissures tend to appear on concrete when it is subjected to flexural and tensile loading due to its low toughness [3]. However, cracks can develop in concrete slabs due to a number of other reasons such as loss of water from evaporation, resulting in plastic shrinkage and reduction in the surface water due to the hydration process. Additionally, decrease in temperature after setting of the concrete leads to thermal contraction. Furthermore, loss of water in the hardened state leads to drying shrinkage, which results in cracks as well as reaction of hydrated Carbon dioxide (CO_2) in presence of moisture leads to carbonation shrinkage, which develops cracks within the concrete slabs [4, 5, 6, 7].

The need for high strength, crack resistant and lighter concrete has channelled research into various materials as reinforcements such as metallic, polymeric, carbon, glass, nylon and waste tyre fibres as reinforcement material [8]. Use of these materials limits crack propagation and widening in concrete slabs through fibre bridging [9]. Moreover, cracks on concrete slabs not only compromise the structural strength of concrete slabs but also affect the aesthetics making them unacceptable [10]. Cracks which occur within concrete slabs may increase the permeability of the concrete. In the case of steel reinforced concrete slabs, water and air is able to reach the steel through the cracks resulting in premature corrosion.

Concrete is a ubiquitous construction raw material with numerous advantages. However, it has very low tensile strength and toughness. This tends to limit its use in many applications [11]. To overcome this shortcoming, there has been much research carried out over the years in developing high ductility Fibre Reinforced Cement Composites (FRCC). Research carried out by Ostartag [12] showed that bridge approach slabs are deteriorating at a much faster rate than expected resulting in a massive need for repairs and premature replacement of concrete slabs. This severe cracking is as a result of impact loading, with the durability further affected by frost action and corrosion. Besides, development of cracks in bridge approach concrete slabs is also prevalent in slabs that have just been recently put up [12]. The tendency of cracking of concrete slabs resulting in reduced load bearing capacity indicates the need of reinforcement material that can increase the durability of concrete slabs and lower maintenance costs.

Brittleness of concrete can be reduced through the use of discontinuous fibres to produce Fibre Reinforced Cement (FRC) [13]. In the FRC, numerous small fibres are dispersed randomly within the concrete mixture, thereby improving the strength properties of concrete slabs [14]. Furthermore, macro polymer fibres have been used for preventing both early age and drying shrinkage cracks [15]. In this regard, research has been carried out into reinforcing concrete by use of fibres from asbestos, polymers, glass and steel [16]. Introduction of fibres changes the quasi-brittle performance of concrete, preventing plastic shrinkage cracks in fresh concrete [17], while inhibiting the transformation of micro cracks to macro cracks in hardened concrete slabs. However, the challenge with introducing fibres in concrete is the high cost associated with producing the fibres. This at times, leads engineers to prefer using thicker unreinforced concrete slabs for greater strength [16]. Yet, this strategy of using of thicker concrete slabs leads to an undesirable increase in the weight of the concrete slabs and cement quantity required in the mixture.

Research on the use of natural and synthetic fibres as reinforcement in cement based composites has been reported by various studies. Natural fibres are preferred for reinforcement in concrete slabs due to their relatively low cost, abundance [18]. However, natural fibres have variations in their strength properties within the individual fibres, making them undesirable for concrete slab reinforcement. On the other hand, synthetic fibres have homogenous strength properties within individual fibres. Furthermore, due to their high strength, synthetic fibre polymers allow the mitigation of the inherent weaknesses of concrete composite slabs [19]. In general, fibres are effective means of increasing shock resistance, toughness and resistance to plastic shrinkage of concrete [20]. Therefore, this study gives a review of synthetic polymeric fibre reinforced concrete slabs and their effects on the mechanical properties.

2. FIBRE REINFORCED CONCRETE

Fibre Reinforced Concrete (FRC) is defined as composite material consisting of cement, sand, coarse aggregate, water and fibres [1]. Fibres have been in use as reinforcement material in construction from the ancient times. Horsehair was used in mortar and straw in mud bricks as reinforcement materials [21]. Randomly distributed short fibre reinforcements are used to improve the brittle characteristics of concrete slabs. Fibres are used to control the initiation and propagation of cracks within concrete slabs[22, 23]. FRC have been used on concrete slabs, architectural panels, precast products, offshore structures, structures in seismic regions, thin and thick repairs, crash barriers as well as hydraulic structures [24]. Concrete slabs are sometimes reinforced with steel bars to increase the tensile strength to counter the lack of ductility of concrete. However, the use of fibres has an added advantage, in that; it produces concrete slabs with more homogenous tensile properties and better micro cracking behaviour [25].

FRC strength is dependent on the fibre mechanical properties, which include the interface between fibre and matrix, aspect ratio (l/d), elastic modulus, the quantity and orientation of the fibres within the matrix [26, 27, 28].

Furthermore, the geometry and shape of the fibre is capable of amplifying the ductility, impact resistance, fracture energy, fire resistance and durability of concrete slabs [29].

Synthetic polymeric fibres have gained popularity due to their toughness, post cracking load carrying capacity and higher deformation at peak load. Additionally, these fibres have a significant attraction due to their low cost, weight and good resistance to corrosion and acids [30, 31]. It is worth noting that, steel fibres are also commonly used as reinforcement in concrete. Though, for volume fractions>1%, the density of the concrete slab increases significantly[32, 33, 34]. Moreover, steel fibres tend to corrode, and this negatively affects the durability and performance of the concrete slabs [35, 36].

Industrial and agricultural waste products in the form of fibres have been successfully added to concrete slabs, to increase their strength. Fibres such as carpet waste, bottling waste, sisal and flax waste have been successfully added to the concrete mixture [37]. The use of waste fibres assists in alleviating the challenges associated with their disposal. Disposal of synthetic fibres in dumps is not environmentally friendly due to the possibility of their breakdown to microplastics. Microplastics find their way into the food chain and are harmful to organic life.

Concrete slabs are subjected to static load as well as short term dynamic loads. Short term dynamic loads can be from projectiles, wind gusts, earthquakes and vibrations. The most common method to improve the impact load resistance of concrete slabs is through the use of randomly oriented fibres [38].

3. WORKABILITY OF CONCRETE PASTE CONTAINING FIBRES

Concrete workability can be defined as the effort required to manipulate and place a freshly mixed paste of concrete with minimum loss of homogeneity [39]. Workability has a direct bearing on the consistency, flowability, pumpability, compactibility and harshness of the concrete paste [40].

There exists intricate and non-linear interactions between the mechanical characteristics of the concrete slabs and constituent ingredient properties that make up the concrete paste [41, 42, 43]. The workability of the concrete paste containing fibre reinforcement is dependent on the fibre loading percentage and fibre aspect ratio. Aruna [18]study reported that with increase in fibre volume fraction and fibre length, there is a reduction in the workability of concrete. The author established that for fibre volume fractions of <3% and fibre length <50mm, the concrete paste can be manually compacted without balling [18]. On the contrary, research carried out by Wilinki et al [19] reported that for fibre loading>0.3%, there are serious problems in concrete paste homogeneity and workability. The variances between the findings of the two authors [18, 19] may be attributed to the different aspect ratios of the fibres used in their studies.

Ismail et al [44] claimed addition of Polyethylene Terephthalate (PET) fibres in concrete increased the workability of concrete. Though, studies by Wilinski et al [19] and Aruna [18] claimed that addition of PET fibres improved slump of concrete but decreased its workability. Wilincki et al [19]study concluded that the concrete slump is dependent on the fibre volume fraction. As the fibre volume fraction increases, the slump decreases significantly. According to study by Wilincki et al [19], the use of 0.1% PET fibre in concrete gives slump value of 50mm whereas, 0.3% PET fibre gives slump value of 10mm.

Thirumurugan et al [45]study reported that workability of concrete decreases with increase in the fibre volume fraction of polypropylene fibres. Though, this can be overcome by the addition of water reducing admixtures. Yet, use of admixtures leads to reduction in compressive strength of the concrete slab [45]. Saadun et al [25] research concluded that addition of 1kg/m^3 of polypropylene fibre gave a slump value of 60mm.

Preti et al [46]study reported that higher volume fractions of polypropylene fibres in concrete slabs reduced the consistency of the concrete paste. For 0.5% fibre content, the workability was reported as high on workability scale. However, at 1% fibre content the workability is considered to be medium. Generally, polypropylene fibres are used in concrete as secondary reinforcement at low fibre fraction levels (0.1 to 0.2%). As a result, the effect on workability is low due to the low fibre loading. However, the slump is significantly improved[47]. Yet, not much research has been done to determine the effect of varying polypropylene aspect ratio on the workability of the concrete paste.

Study by Balaguru [14] reported that if high volume fraction of synthetic fibres is used in concrete slabs, there is a reduction in concrete paste consistency. However, the workability can be improved by increasing the water ratio [14]. Though, this tends to reduce the compressive strength of the concrete slab. This reduction in compressive strength is attributed to an increase in entrapped air within the concrete mixture creating voids. However, not much research has been carried out to find the optimum amount of water to high fibre loading that can be added to concrete slabs to give optimum flexural and compressive strength.

The general trend in research [46, 10, 14, 48] shows, there is a decrease in the ease of placement and consistency of concrete paste containing polymeric fibre reinforcement. This is attributed to increase in the amount of entrapped air voids due to the presence of fibres. The increase in air voids has an adverse effect on the workability of the concrete [10]. Though; the slump value improves with addition of fibres into the concrete paste.

4. SYNTHETIC POLYMER FIBRE REINFORCED CONCRETE

A number of synthetic fibres namely; polypropylene, polyethylene terephthalate, olefin and polyamide fibres have been used successfully in reinforced concrete slabs. The effects of these synthetic fibres on the strength properties of concrete slabs are reviewed under the following four subheadings;

4.1 Polypropylene Fibre Reinforced Concrete

Polypropylene is a thermoplastic polymer, which is commonly used in bundling materials, stationery, amplifiers, research facility gear and a number of car segments [49]. These fibres are produced in large quantities, and are the fourth most produced synthetic fibres after polyesters, polyamides and acrylics. Polypropylene fibres have been used as reinforcement materials for concrete slabs with success in improving its energy absorption capabilities. Polypropylene fibres were first used as reinforcement in concrete slabs intended for the construction of blast resistant buildings [51]. Generally, polypropylene fibre reinforced concrete is used commercially in secondary temperature shrinkage reinforcement, overlays, pavements and slabs. Other common applications include flooring systems, crash barriers, precast pile shells, shotcrete for tunnel linings, rigid pavement as well as self-compacting concrete[52, 53]. Largely, polypropylene fibres are commercially utilized at relatively low volume fractions in order to control plastic shrinkage cracking of concrete slabs [54].

Mazaheripour et al [55] studied the use of polypropylene fibres in concrete slabs. The author noted that high volume fraction of polypropylene fibres increased both the tensile and flexural strength of the concrete slabs significantly. However, not much research has been done on the optimization of the volume fraction of the polypropylene fibres in concrete slabs [20].

Fibrillated fibres are fibres, which have been extruded into very fine and slender fibrils. The fibrils offer outstanding mechanical bond strength in concrete due to their irregular and square shape. Fibrillated polypropylene fibres have been recommended for use in paving concrete as they reduce plastic shrinkage and permeability, increase impact and

abrasion resistance [56]. Generally, fibre loading for paving concrete is 0.1%. Though, some research has been carried out with up to 7% polypropylene fibre loading. However, fibre loading >7% reduces the concrete paste workability significantly [56]. Unfortunately, there has not been much research on the use of hybrid polypropylene fibre reinforcement in concrete slabs. That is, the use of fibrillated polypropylene fibres together with fibrillated fibres and their effects on strength properties of concrete slabs.

Saduun [25] study reported that low volume fractions of polypropylene fibres of between 0.05 and 0.5% have a negligible effect on the compressive strength of fibre reinforced concrete[25]. However, other studies by Zollo [47] and Mindess and Vondran [57] gave contradictory conclusions on the effects of polypropylene fibres on the compressive and flexural strength of concrete[57, 58]. Moreover, the differences in the conclusions from the two authors on the effects of fibres on strength may be attributed to variations in matrix composition, type of polypropylene fibre and conditions of polypropylene fibres manufacture. Additional studyby Saadun [25] on flexural strength of concrete reinforced with polypropylene concluded that the flexural strength increased as fibre volume fraction of polypropylene increases. At 1kg/m^3, the flexural strength is 3.50 MPa, whereas at 2kg/m^3, the flexural strength is 3.92MPa [25]. Another study by Dharan and Aswathy [10]reported that the best flexural strength of polypropylene fibre reinforced concrete slabs occurs at 1.5% volume fraction. After 28days of concrete curing time, the resulting flexural strength from the aforementioned ratio is 5.71 MPa, which is an increase of 31.57% over unreinforced concrete.

Mohod [56] carried out further research to establish the composition of fibre volume fraction of polypropylene fibres in concrete slabs that gives the optimal flexural strength. The author recommended the use of 0.1% volume fraction of polypropylene fibre in paving slabs. Besides, fibre volume fraction exceeding 0.5% requires the use of admixtures [56].

Saadun et al [25] reported that the compressive strength of polypropylene fibre reinforced concrete decreased with increase in fibre volume fraction. At 1kg/m^3, the compressive strength is 34.87MPa while at 2kg/m^3 the compressive strength is 28.08MPa [25]. However, another research carried out by Mindess [59] concluded that long term compressive strength increased by 25% at 0.5% polypropylene fibre volume fraction. Furthermore, the same study by Mindess [59] reported an increase in the short term compressive strength at low polypropylene fibre loading.

Dharan and Aswathy[10] studied the effects of polypropylene fibres on the compressive strength of concrete. The study reported that fibres increased the short term compressive strength marginally. However, polypropylene fibres have a more significant effect on the long term compressive strength of the concrete. Dharan and Aswathy[10] concluded that the best fibre volume fraction is 1.5% which gives a 28 day compressive strength of 46MPa. This volume fraction gives a 17% increase in compressive strength over unreinforced concrete. This optimum fibre volume fraction of 1.5% was confirmed by another study by Ramujee [60]. Hughes [61] study established that compressive strength of concrete containing polypropylene fibres decreases with increase in fibre volume fraction. On the hand, the study reported improved flexural properties with increase in polypropylene fibre volume fraction. Further study by Parveen [62] noted an increase in compressive strength at low fibre loading of up to 0.2%. Thereafter, there is a reduction in compressive strength with increase in fibre loading beyond 0.2%

Jassim [50] study showed the effects of polypropylene fibres on concrete strength as shown in figure 1. The study concluded that polypropylene fibres increase the short term (<28days) compressive strength. On the other hand, the long term compressive strength (>28days) reduces with increase in fibre loading. However, the effects of fibre length in

conjunction with fibre loading on compressive strength in concrete slabs have not been fully researched.

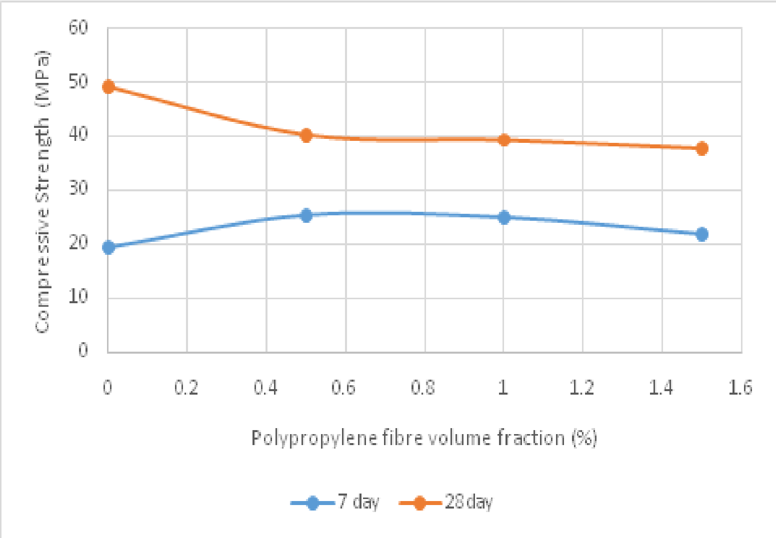

Figure 1: Effect of Polypropylene Fibre Loading on Compressive Strength of Concrete [50].

Another study by Mukhopadhyay [63]reported that there is a dense microstructure around polypropylene fibre in FRC, which gives a strong interfacial adhesion and anchoring of the fibres within the cement matrix. However, there has not been much research into the interfacial adhesion strength of different synthetic fibres.

4.2 Polyethylene Terephthalate Fibre Reinforced Concrete

Polyethylene Terephthalate (PET) is a thermoplastic used mainly in textiles fibres, beverage and other liquid containers [64]. PET fibres have generated a lot of attention in the FRC industry. This is due to the fact that the fibres can be easily mixed into the concrete paste. Ataei et al [65] studied the compressive strength effect of recycled PET particles in concrete. The research reported a decrease in compressive strength after the addition of PET particles. This occurrence was attributed to the weak cohesion between the particles and the cement resin. Rahmani et al [66]gave a similar conclusion of a general decrease in compressive strength with the addition of PET particles to concrete. Rahmani et al [66] reported that the compressive strength of PET particle reinforced concrete had an increase in compressive strength of 8.86% at 5% particle mass fraction. However, at 10% PET particle mass fraction, the compressive strength was found to remain the same as that of unreinforced concrete [66]. Whereas, the compressive strength decreases to 5.14% at PET particle mass fraction of 15%.

Choi et al [67]also studied the effects of increasing the mass fraction of PET particles on the compressive strength. The author showed there was a decline in compressive strength with increase in mass fraction of PET particles. At 50% PET particle mass fraction, the loss in compressive strength was found to be 14.52%. Whilst, at 75% PET particle mass fraction, the compressive strength loss was 33.06% in reference to unreinforced concrete slabs [67]. The conclusion reached by Choi et al [67] work was consistent with that of previous studies by Ataei et al [65] and Rahmani et al [66].

Mukhopadhyay [63] studied the use of hybrid PET and steel fibres to give superior toughness to concrete slabs [68]. The study reported an increase in ultimate tensile strain capacity at peak with an increase in PET fibre loading. However, beyond a certain fibre loading, the ultimate tensile strain starts to decrease. Further, the author noted that increase in PET fibre length improves strain hardening and multiple cracking behaviour. This improvement increases theultimate strain capacity of the concrete slab. However, the study failed to account for the critical length phenomenon,

whereby, the strength of the concrete starts to reduce at certain fibre lengths. Besides, not much research has been done into the use of hybrid fibres consisting of PET and other synthetic polymer fibres such as polypropylene in concrete slabs.

Ismail et al [44]studied the flexural strength properties of waste PET particle reinforced concrete. This study concluded that at 20% PET particles mass fraction there was a decrease of 30.5% in flexural strength. This decrease in flexural strength was attributed to a reduction in adhesive strength due to the hydrophobic nature of PET. Furthermore, the decrease in flexural strength can also be attributed to the elastic nature and non-brittle loading characteristics of the plastic aggregate. Nonetheless, the flexural strength can be increased by the use of PET fibres, which have a high aspect ratio. However, more research needs to be carried out to establish PET aspect ratios which give optimal flexural strength properties.

4.3 Olefin Fibre Reinforced Concrete

Olefin fibres have good tensile properties, good abrasion resistance and excellent resistance to chemicals. The tensile strength of polyolefin fibres is above 400 MPa. Furthermore, these fibres tend to form a good bond within concrete when used as reinforcement material due to their rough surface.

Olefin macro fibre volume fractions commonly used in concrete range from 0.3 to 1.5% [59]. Reviewed literature by Neeley and O'Neil [69], Ramakrishnan [70] and Hamou et al [71]showed that the proper use of olefin fibre in concrete slabs gives similar strength to that of steel fibre reinforced concrete at much lower weight. In addition, the use of olefin fibre has been proved to give 13% increase in strength than unreinforced concrete slabs. Moreover, olefin fibre reinforced concrete reduces the propagation of cracks by up to 70% in comparison to unreinforced concrete [72]. Further, research carried out by Lin et al [72]concluded that olefin fibre reinforced concrete of similar volume fraction has impact strength, which is two times stronger than that of steel fibre reinforced concrete slabs. This superior strength of olefin fibre makes the olefin reinforced concrete slabs fourteen times greater in impact strength than unreinforced concrete [72]. The high strength of the concrete slabs can be attributed to the remarkable good bond generated between the fibres and the concrete due to their rough surface. Yet, not much research has been done on the effects of other geometries of olefinfibres in concrete slabs such as crimped fibres.

It is worth noting that there exists a threshold volume fraction, of which, the compressive strength becomes less than that of typical unreinforced concrete [73].

4.4 Polyamides Fibre Reinforced Concrete

Polyamide (PA) fibres have superior tensile strength to most synthetic fibres including polypropylene and polyolefin fibres which are commonly used in concrete [74, 7, 75]. The use of micro PA in concrete gives concrete with superior properties which resists early age shrinkage cracks. Macro PA fibres are effective in enhancing the axial load capacity and post peak behaviour of concrete [28]. PA fibre reinforced concrete is durable, resistant to corrosion effects and has good workability. PA is commonly referred to as nylons, and contains the amide group [-CO-NH-] in their main chain.

Research carried out by Guler [28] concluded that the ductility and toughness of concrete reinforced with PA increased significantly. However, there was only a marginal improvement in the compressive strength. PA fibres can be used successfully at volumes fractions >0.5% as alternative to steel fibre reinforced concrete.

Walton and Majumdar [76] study showed that PA fibres in small amount improved substantially the impact resistance on concrete slabs. However, PA fibres have only marginal improvement on the tensile or flexural strength. The high impact strength is attributed to the stretching and pulling out of the fibres which occurs at large strains after the failure of the

cement matrix at lower load. On the contrary, not much research has been done using specific PA fibres such as nylon and nylon 6, 6, to determine the effects of varying volume fraction as well as fibre length on the properties of concrete slab.

5. FAILURE MECHANISMS OF FIBRE REINFORCED CONCRETE SLABS

Failure of a concrete slab material is the stage, when it ceases to perform in a satisfactory manner for the specific end use. However, characterisation of the failure mechanisms of concrete slab material is difficult due to the complexity of their failure modes [77]. For FRC, the main benefit obtained from inclusion of fibres in concrete occurs after matrix cracking.

The fibre parameters, which govern and have a significant effect on crack control and failure inhibition are fibre surface area, bond strength, fibre pull out strength, fibre rupture strengths as well as fibre aspect ratio [2]. Yet, the predominant mechanism of energy dissipation during concrete slab failure is fibre pull out. This is the failure mode which increases the fracture toughness of the slab significantly [78].

Failure of fibre reinforced concrete slabs is a multi-stage process, which is dependent on the internal structure of the multiphase materials. The main factors that govern the effect the fibres have on the strength properties of the concrete slabs include the physical properties of the fibre, the fibre and interface bond, the fibre volume fraction as well as the orientation of the fibres within the concrete. Still, not much research has been done in optimising the aggregate material and fibre volume fraction to obtain the best concrete slab strength properties.

5.1 Fibre Mechanics

Fibres such as steel wire, polyester fibres or aromatic fibres can be classified as tough as they undergo non elastic deformation after yielding. Furthermore, the deformation mechanisms include plastic necking and inter fibrillary splitting in synthetic polymer fibres. As a result, these fibres tend to show a high resistance to surface damage compared to brittle fibres. Figure 2 shows the different failure modes of fibres in fibre reinforced concrete slabs.

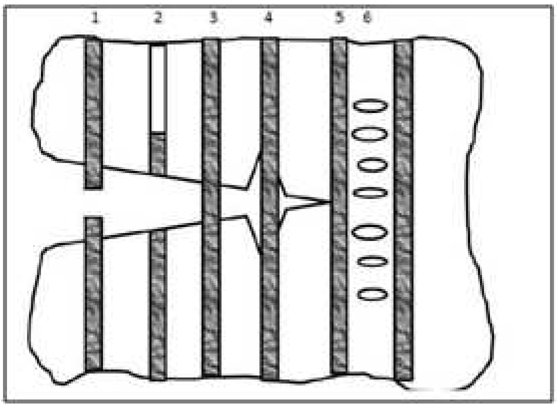

Figure 2: Failure Mechanisms in Fibre Reinforced Concrete Slabs.
1: Fibre rupture
2: Fibre Pull Out
3: Fibre Bridging
4: Fibre/Matrix De-bonding
5: Fibre Preventing Crack Propagating
6: Matrix cracking [48]

When the localised load in a fibre reaches the failure stress, the fibre will break at its weakest point along the fibre length. As a result, the load is then transferred to the neighbouring matrix regions. As the load increases, other fibres may break. However, each fibre can break numerous times without having any noteworthy impact on the overall load bearing

ability of the concrete slab. This fibre ability to withstand the load is due to the ineffective length, which is the short distance with the tensile load supported. The stress in the ineffective length will rapidly build up again until the fibre breaks. This cycle continues increasing the toughness of the concrete slab.

Catastrophic brittle failure can occur, when the fibres are closely spaced and the extra tensile load is transferred to a neighbouring fibre, resulting in it breaking. The local stress concentration is then even higher. If this process is repeated several times, the cross sectional area, where the fibre breaks are occurring will become weak resulting in catastrophic brittle failure [48].

There is a need to optimize the fibre bond within the concrete matrix. If the fibres form a weak bond with the matrix, the dominant failure mode will be fibre slippage. This slippage of fibres lowers the toughness of the fibre reinforced concrete slab, as the fibres will not have much effect on increasing the toughness of the concrete. However, if the bond formed between the fibres and the concrete matrix is too strong, then the failure mode will be dominated by fibre breakage. This breakage of fibres is due to the fibres breaking before they dissipate energy through any fibre slippage. The fibres in such a case will then have a marginal effect on increasing strength properties of the concrete slab.

When a crack travelling in the concrete matrix approaches an isolated fibre, the crack is halted by the fibre. This crack retardation is due to the stiffness of the fibre which inhibits further propagation of the crack. The strength of the fibre is higher than the level of the stress which will be concentrated at the tip of the matrix crack. Crack propagation may occur if the local shearing force acting at the fibre and matrix interface becomes adequately high to allow fibre debonding. During fibre debonding process, the fibre will extend elastically, and subsequent crack propagation will take place while the matrix slides relative to the fibre, as shown in figure 3. This process requires energy which contributes to the toughness of the reinforced concrete slab.

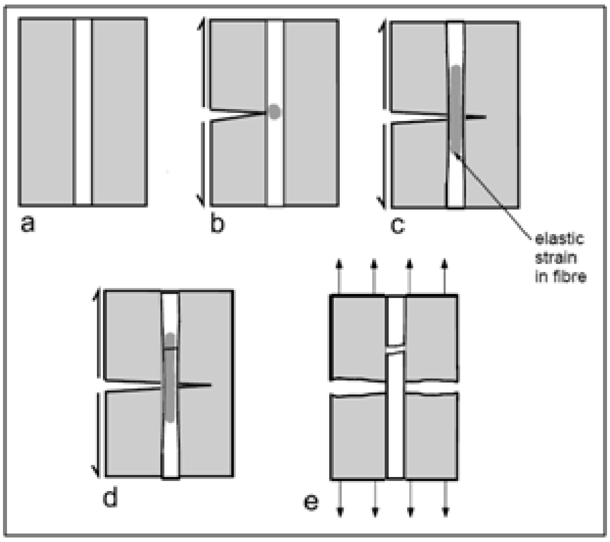

Figure 3: Process of Fibre De-bonding Failure in Concrete [48].

5.2 Fibre Length

The optimization of fibre length in composites results in improved mechanical properties. Shorter fibres can be more evenly distributed in the concrete mixture unlike longer fibres which tend to clump together. Furthermore, the interfacial

bond strength can only be optimized if the fibre length is at its optimum value, such that it provides resistance to fibre pull out and also have enough fibre modulus of rupture to avoid fibre fracture.

The length of fibre determines the failure mode that the composite will have. If the fibre length is longer than the critical length, then fibre fracture is the most prevalent failure mode. Whereas, if the fibre length is shorter than the critical length, then the fibre pull out is the likely failure mode. Fibre critical length is dependent on the ultimate tensile strength of the fibre (σ_f), fibre diameter (d) and the matrix/bond strength or the matrix shear strength abbreviated as τ_c. Besides, the critical length is affected by the diameter of the fibre. Whenever the diameter of the fibre becomes smaller, the critical length of the fibres decreases [79]. Critical fibre length (L_c) is calculated using equation 1 here under;

$$L_c = \frac{\sigma_f d}{2\tau_c} \quad (1)$$

When the critical length L_c is equal to the length of the fibre the optimal fibre load is achieved at the centre of the fibre. If the $L > L_c$ then the optimal fibre load is carried by most of the fibre and is usually the case with continuous filaments. When $L < L_c$ the fibre length is below critical length and thus the optimal fibre load cannot be reached. This shortcoming results in a weaker composite material. A large number of short fibres is effective in bridging numerous micro cracks in the concrete slabs under load and avoid localised strain. Long fibres on the other hand, are of great use in bridging macro cracks at higher loads. Nonetheless, long fibres reduce the workability of the concrete mix significantly. Furthermore, an increase in the fibre length gives a reduction in the bond strength between the fibre and concrete boundary. Fibres exceeding 12mm in length are not suitable for optimum reinforcement of concrete slabs [80]. However, the addition of Mowilith Pulvet re-dispensable co-polymeric powders increases the adhesion of long fibres between the fibre and cement matrix boundary [80]. Though, there has not been much research done into the use of filament synthetic fibres and co-polymeric powders as reinforcement materials in concrete slabs. Despite co-polymeric powders increasing adhesion of fibres to concrete.

Mohd [56] carried out research into the use of polypropylene fibres as reinforcement in concrete slabs. The study established that there is a relationship between fibre length and the maximum nominal size of the aggregate in the concrete mixture. In addition, the study recommended that, the fibre length be at least twice the diameter of the aggregate.

5.3 Fibre Aspect Ratio

One of the most important parameters describing a fibre is its aspect ratio. Aspect ratio is defined as the length of a fibre divided by an equivalent diameter of the fibre [1]. The energy absorption of a concrete composite material increases when the fibre aspect ratio increases. This is due to the fact that a higher aspect ratio gives a greater surface area by having a greater number of fibres in the concrete slab [81].

Sudhikumar [82]study reported that the compressive strength of slurry infiltrated fibrous ferrocement with steel fibre reinforcement reduced, as the aspect ratio increased. A compressional strength of 41.33MPa was reordered for a fibre aspect ratio of 25. Whereas, a compressional strength of 28.29MPa was recorded for an aspect ratio of 50. The study showed that low aspect ratio gives better compressive strength. In addition, the same author studied further the same experiment described in the preceding sentence using polypropylene fibres instead of steel fibres. The study reported a similar trend on the effect of aspect ratio between the two fibres. On the other hand, results on flexural strength and toughness indices showed a consistent trendfor both fibres, with the flexural strength decreasing with an increase in fibre aspect ratio. This decrease in flexural strength may be attributed to the low fibre aspect ratio fibres being able to fill voids producing a denser concrete, which absorbs energy better.

In another study by Sovjak [83], it was established that increase in the fibre aspect ratio in polymeric fibre reinforced concrete slabs leads to an increase of the effective fracture energy. Further, the study established that there is a linear relationship between fibre aspect ratio and effective fracture energy. Nevertheless, research on the effects of aspect ratio on strength properties of concrete slabs for different types of polymeric fibres is not exhaustive.

6. SUMMARY AND DISCUSSIONS

Concrete is a brittle universal construction material with low tensile strength and fracture toughness. Furthermore, cracks develop on concrete when it is subjected to strain in its hardened state, particularly when there is a reduction in water during its plastic state. The cracks on concrete may be attributed to plastic shrinkage, thermal contractions and reaction of hydrated CO_2 in presence of moisture results in carbonation shrinkage. The use of fibres in concrete tends to increases its toughness and durability. Besides, the use of synthetic fibres in concrete improves the fire and thermal resistance due to abrupt change in temperature. For instance, at higher temperatures the fibres melt and are absorbed within the concrete. Moreover, the fibres generate a permeable network to allow gas migration. This migration of gas eliminates any possibility of concrete explosive spalling [84, 85]. Though, very little information on the reduction in explosive spalling using different types of synthetic fibres is available.

FRC strength depends on the fibre properties, interface bond strength, aspect ratio and orientation of fibres within the concrete slabs. The failure of FRC is a multi-stage process which is dependent on the internal structure of the multiphase materials. Most of the reviewed studies were carried out on randomly laid fibres within the concrete slabs. However, not much research has been done to establish the strength effects on various orientations of fibres in concrete slabs. On the other hand, synthetic fibres have gained significant popularity due to their low weight and resistance to corrosion and acids [26, 31]. Furthermore, there is great potential for the use of recycled synthetic fibres especially PET as reinforcement material in concrete. In this regard, there is need for further research into the use of waste fibres from textiles and other polymeric materials for purposes of concrete reinforcement.

The workability of concrete mixture containing fibres is dependent on the percentage of fibre loading and aspect ratio. Reviewed literature by Aruna [18], Wilinski et al [19], Thurumurugan and Sivakumar [45] and Patel [46]proved that the workability of the concrete paste tends to reduce with increase in the percentage of fibre loading. Probably, due to the increase in air voids within the concrete mixture arising from the introduction of reinforcement fibres [10]. However, the low workability can be overcome by increasing the water ratio. Though, increasing the amount of water ratio has a negative effect on the compressive strength of the concrete slabs. This reduction in compressive strength is due to the creation of voids within the hardened concrete. Unfortunately, the effect of water ratio and fibre loading on the final strength properties of the concrete slabs is not known. On the other hand, besides the slump value of concrete mixture increasing with increase in fibre loading it decreases the workability.

Polypropylene fibre has been used as reinforcement material in concrete slabs to improve energy absorption capabilities [51]. Reviewed literature by Dharan and Aswathy [10] and Ramujee [52]showed that the optimal fibre volume fraction for polypropylene for short term compressive strength is 1.5%. Beyond this 1.5% volume fraction there is gradual decrease in compressive strength. This decrease in compressive strength is due to the fact that as there is development of the microstructure of the concrete as hydration advances. Since the transition zone initially filled with water around, the fibres fails to develop into a dense microstructure. Hence, formation of cavities that lead to significant decrease in compressive strength of FRC slabs. In contrast, as fibre volume fraction increases beyond 1.5% the flexural strength

increases. Though, not much research has been done on other types of polypropylene fibres such as fibrillated fibres, they show good results when used in blast resistant concrete slabs [56].

The use of PET fibres as reinforcement material in concrete slabs increases the degree of toughness[63]. Fibres alter the failure mode of concrete increasing its ductility. Short and discrete fibres should be uniformly distributed and randomly oriented within the concrete mixture for maximum strength. Despite, PET particles giving low concrete slab strength due to their lower aspect ratio than PET fibres, they have been widely used as reinforcement material. However, there is scanty information on hybrid composites consisting of PET and other synthetic fibres including additives like fly ash.

Polyamide fibres can be used at volumes fractions >0.5% successfully in concrete, as an alternative to steel fibre reinforcement [72] . Polyamide fibre due to their superior mechanical properties produces concrete slabs with good strength and low weight. Whereas, the volume fraction of olefin fibre reinforcement used in concrete ranges from 0.3 to 1.5% [59].

The failure of synthetic fibre reinforced concrete is dependent on the fibre properties which include its mechanical properties, fibre length, aspect ratio and fibre loading. Though, data on optimisation of these fibre properties in concrete slabs is not exhaustive.

7. CONCLUSIONS

Reinforcing concrete slabs with synthetic fibres increases its structural integrity. To increase strength, short and discrete fibres should be uniformly distributed and random within the concrete mixture. Though, there has not been much research done to establish the effects of varying fibre aspect ratio and loading on the strength of various polymeric reinforced concrete slabs. Furthermore, there has not been much research done into the use of PET waste fibres in concrete slabs. Additionally, there is need to carry out research into hybrid fibre reinforced concrete slabs composites containing different types of synthetic fibres and additives.

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